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Decentralised carbon footprint analysis for opting climate change mitigation strategies in India

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ABSTRACT

Carbon footprint (CF) refers to the total amount of carbon dioxide and its equivalents emitted due to various anthropogenic activities. Carbon emission and sequestration inventories have been reviewed sector-wise for all federal states in India to identify the sectors and regions responsible for carbon imbalances. This would help in implementing appropriate climate change mitigation and management strategies at disaggregated levels. Major sectors of carbon emissions in India are through electricity generation, transport, domestic energy consumption, industries and agriculture. A majority of carbon storage occurs in forest biomass and soil. This paper focuses on the statewise carbon emissions (CO_2, CO and CH_4), using region specific emission factors and statewise carbon sequestration capacity. The estimate shows that CO_2, CO and CH_4 emissions from India are 965.9, 22.5 and 16.9 Tg per year, respectively. Electricity generation contributes 35.5% of total CO_2 emission, which is followed by the contribution from transport. Vehicular transport exclusively contributes 25.5% of total emission. The analysis shows that Maharashtra emits higher CO_2, followed by Andhra Pradesh, Uttar Pradesh, Gujarat, Tamil Nadu and West Bengal. The carbon status, which is the ratio of annual carbon storage against carbon emission, for each federal state is computed. This shows that small states and union territories (UT) like Arunachal Pradesh, Mizoram and Andaman and Nicobar Islands, where carbon sequestration is higher due to good vegetation cover, have carbon status >1. Annually, 7.35% of total carbon emissions get stored either in forest biomass or soil, out of which 34% is in Arunachal Pradesh, Madhya Pradesh, Chhattisgarh and Orissa.

Contents

1. Introduction

Carbon footprint is a synonym for emissions of carbon dioxide or other greenhouse gases (GHGs) expressed in carbon dioxide equivalents. This has been used as an environmental indicator to understand and quantify the main emission sources and it constitutes as an effective tool for energy and environment management. It helps us to determine the quantity of emission from different carbon emitting sectors, which in turn is useful for

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quantifying the impact of human activities on the environment and global climate. Carbon dioxide concentration in the atmosphere has been rising alarmingly in the post industrial revolution era and the current level is about 379 ppm (ppm = parts per million) compared to 280 ppm earlier (pre industrialisation). The Planning Commission of the Government of India advocates in the 12th Five-Year Plan of the country for low carbon growth. The proposed actions will reduce India's emission intensity from 20% to 25% by 2020 with respect to the emissions in 2005. This includes policy interventions to reduce emission intensity through fuel-efficiency standards, green building codes and energy efficiency certificates. In this context, numerous challenges that are to be addressed include the burgeoning population coupled with urbanisation, industrialisation and provision of infrastructure and transport facilities. This necessitates decentralised mitigation strategies to minimise carbon emissions which require sector wise and region wise inventory of GHG emissions. National GHG emission inventories based on United Nations Framework Convention on Climate Change (UNFCCC) aid in this regard for evolving mitigation policies and action plans. The national inventories of emission and sequestration provide a general guideline for assessing the mitigation alternatives [1]. Statewise estimates of emission inventories help to understand the major sources and sinks of carbon at regional levels. It also helps to understand the carbon flux and facilitate in the implementation at local levels by sector wise mitigation policies.

Carbon footprint at local level helps in aligning climate policy with local development, sharpening the awareness of municipal stakeholders about the links between local activities and climate change and local benchmarks against a city's own historical emissions [2]. Environmentally extended input–output analysis (EE-IOA) has long been recognised as a useful top–down technique to attribute pollution or resource use to final demand in a consistent framework [3–5]. Interest for EE-IOA has increased with the significant increase of interest in consumption-based emission and resource accounting. Consumption-based accounting focussing on GHG has become relevant for policy and decision making. This approach, where all emissions occurring along the chains of production and distribution are allocated to the final consumer of products, is seen as providing several opportunities. Consumption-based accounting (CBA) complements the territorial-based approach [6,7] by including all drivers of GHG emissions associated with consumption.

Consumption based GHG emission inventory varies with income and urbanisation. Carbon footprint of twelve metropolitan cities, with inter and intra variability in metropolitan areas and found Delhi has lowest per capita CF of 0.70 metric ton with lowest per capita income of $950 whereas Los Angeles and New York both with higher per capita income of $46,040 have CF of 3.69 and 1.94 metric ton respectively due to higher consumption pattern [8]. Urbanisation has changed our lifestyle as well as consumption pattern. Carbon footprint analysis of metropolitan

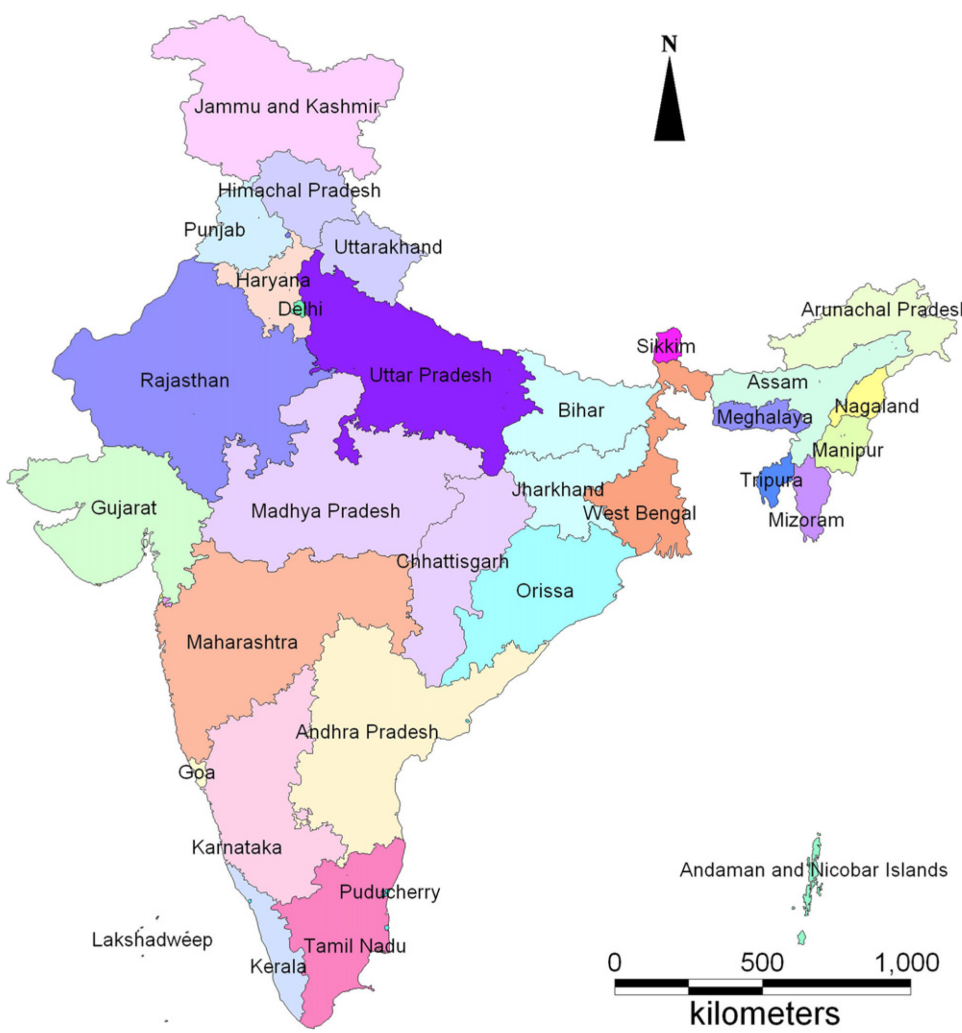


Fig. 1. State and UT of India.

America using national database through transportation and residential sectors show that per capita carbon emissions vary substantially as large metropolitan areas offer greater energy and carbon efficiency [9]. Study on housing sectors reveals that wood intensive houses store more embodied carbon compared to normal modern houses [10]. Current Indian population has crossed 1200 million according to the Directorate of Census Operation, with approximately 28% living in urban areas. This share is predicted to increase to about 40% by 2021 [11]. India and China account for 51% of incremental world primary energy demand in 2006–2030 as per WEO [12]. Urban areas in these countries are the prime energy demand and also GHG emission centres. An inventory of the energy status and carbon emissions of 54 South Asian cities, including 41 cities from India, based on the city energy consumption and related carbon emissions show that major metropolitan/urbanized and industrialised regions have higher GHG emission [1,13].

The demand for energy has been increasing with urbanisation and burgeoning population. Electricity, fuel wood, kerosene and Liquefied Petroleum Gas (LPG) are used for cooking and lighting in rural and urban areas in India. Estimates indicate that in urban areas, per capita per month consumption of firewood, electricity, kerosene and LPG are 6.65 kg, 22.32 kWh, 0.22 l and 1.81 kg, respectively. The total installed capacity of electricity generation has increased from 16 GW in 1971 to 174 GW in 2009 [14].

Socio-economic growth coupled with the boost in the infrastructure sector during the post globalisation era has enhanced the growth of cement and steel industries. The production of cement has increased to 181.61 mt in year 2008–09 as against 168.31 mt in year 2007–08. Similarly, the crude steel production shows annual growth of 1.23% [15]. However, these increases in cement and steel production have enhanced carbon emissions surpassing natural sequestration of carbon.

Forest vegetation and soil are major carbon sinks. In 2005, India's forest cover was spread in an area of 677,088 km^2 and it accounted for 20.6% of the total geographical area of the country, whereas, tree cover accounted for 2.8% of India's geographical area [16,17]. The greater forest cover is proportional to greater carbon storage because forest soil has the potential to sequester carbon. Also, improvements in agricultural practices would increase the quantity of organic carbon in soil [18].

In this context, decentralised inventory of carbon emission via-a-vis sequestration potential at disaggregated levels would help in implementing carbon capture strategies. This requires sector wise analysis of sources and sinks at disaggregated levels and region specific mitigation measures depending on the sources. The focus of this work is to develop the state wise carbon balance inventory for India. Electricity generation, transport, industries, domestic energy, agriculture and waste disposal sectors are considered for emission estimates. Forest biomass, forest soil and agricultural soil are considered for carbon sequestration. This is done based on the compilation of data from each sector in all states of India and through the review of the emission and sink experiments carried out in India and India specific IPCC default emission factors [1,19,20].

Table 1
Emission coefficients used in electricity production.

	CO_2	CO	Reference
Coal		3.392 g/kWh	[22]
Coal	0.846 t/MWh		[23]
Natural gas	1980 t/Mcum		[24]
Diesel	3.19 t/t		[24]

2. Methods

Sector wise emission factors: Data pertaining to the sector wise activities for each state were compiled from published literatures and also respective government agencies. The sector wise carbon status has been computed for all federal states in India (Fig. 1). Sector wise total emission for a particular GHG is computed by considering activity level and emission coefficient as given by Eq. (1) [1,20,21].

$$\text{Total emissions} = \sum_{\text{State}} \sum_{\text{Source}} \sum_{\text{Sectors}} [\text{activity level} \times \text{emission coefficient}] \quad (1)$$

- *Electricity generation*: Region specific emission factors for coal thermal power plant were compiled from published literatures [22,23]. However, emission factor specific for gas and diesel thermal power plants are not available and hence region specific factor combustion of natural gas and diesel have been used as listed in Table 1 [24].
- *Transport*: Region specific emission factors of road transport, based on the type of vehicle are listed in Table 2 [25–30]. As per the automobile technology prevalent in India, diesel is used as fuel in buses, mini buses, taxi, trucks, lorries, light motor vehicles (goods), trailers and tractors, while two wheelers, light motor

Table 2
Number, annually average covered distance (km) and emission factors (g/km) for road vehicles.

	Bus	Omni buses	Two wheelers	Light motor vehicles (Passenger)	Cars and jeeps	Taxi	Trucks and lorries	Light motor vehicles (Goods)	Trailers and tractors	Others[a]	Reference
Number	594,059	173,534	51,921,973	2,167,324	8,549,287	901,889	2,372,702	1,375,782	2,372,702	357,569	[85]
AACD[b] (km)	100,000	100,000	6300	33,500	12,600	12,600	57,500	63,000	2100	46,400	[32,33]
CO_2	515.2	515.2	26.6	60.3	223.6	208.3	515.2	515.2	515.2	343.9	[25]
CO	3.6	3.6	2.2	5.1	1.98	0.9	3.6	5.1	5.1	3.9	[27]
NO_x	12	12	0.19	1.28	0.2	0.5	6.3	1.3	1.3	3.9	[27]
CH_4	0.09	0.09	0.2	0.2	0.2	0.01	0.09	0.09	0.09	0.1	[26]
SO_2	1.4	1.4	0.013	0.03	0.05[c]	10.3[d]	1.4	1.4	1.4	1.9	[28]
PM	0.6	0.6	0.05	0.2	0.03	0.07	0.3	0.2	0.2	0.2	[27]
HC	0.9	0.9	1.42	0.14	0.25	0.13	0.87	0.14	0.14	0.5	[27]

[a] Average of above value are used for others.
[b] Annually average covered distance (AACD).
[c] [71].
[d] [22].

vehicles (passenger), car and jeeps use unleaded petrol. In Delhi, most of the buses and mini buses and 5% of total cars and jeeps also use CNG (Compressed Natural Gas) [31]. CO, HC, NO_x and PM emission coefficients from CNG based buses were 1.77, 0.88, 2.81 and 0.032 g km^{-1} and for cars and jeeps, it were 0.78, 1.55, 0.92 and 0.02 g km^{-1}, respectively [27]. Table 2 lists vehicle type-wise annual average distance travelled [32,33]. Annual utilisation of buses, mini buses, two-wheelers, light motor vehicles (passenger), cars and jeeps, and taxi were assumed to be 100000, 100000, 6300, 33500, 12600 and 12600 km, respectively [32]. Similarly, for trucks and lorries, light motor vehicles (goods), trailers, and tractors 25000 to 90000, 63000 and 21000 km per year were assumed [33].

- *Industries*: Based on consumption of coal and its type, region specific emission factor for computing CO_2 emission from cement and steel sector (Table 3) has been used.
- *Domestic energy*: Emissions from the domestic energy consumption depend on the type and quantity of energy consumption. Fuelwood and bio-residues, kerosene, LPG and electricity are generally used in the Indian domestic sector. Electricity is not considered here to avoid the double counting of emission from electricity. Region specific emission factors [34,35] were used to compute emission from fuelwood and bio-residues. Net Calorific Value (NCV) was used to compute CO_2 emissions from kerosene and LPG [19] and emission factors are given in Table 4.
- *Agriculture*: Agricultural residue burning, livestock and rice cultivation are three activities which contribute in carbon emission. Emissions from agriculture sector were quantified based on IPCC approaches [20] as listed in Table 5. Emissions from agricultural residue burning for the year 2005/06 were computed based on the crop data considering standard crop residue ratio [20,36,37], dry matter fraction [20,38,39,40], fraction actually burned [20,21,41,42], fraction oxidised [20], CH_4 emission factor [43–45], CO emission factor [43–45] and CO_2 emission factor [43,44].
- *Livestock*: Emission from livestock was calculated using region specific emission factors for enteric fermentation and for manure management of bovines compiled from various literatures [46,47] for 2003 are listed in Tables 6–8. Emission factor (EF) of 2.83 to 76.65 kg/head/year for enteric fermentation, 0.8 ± 0.04 to 3.3 ± 0.16 kg/head/year for manure management

Table 3
Emission factor used in industries.

	CO_2 (t/t)	Reference
Cement industry	0.5	[90,24]
Coking coal combustion (steel sector)	2.05	[24]
Coal combustion	1.76	[24]

Table 4
Emission factor used in domestic energy consumption.

	CO	CO_2	CH_4	Reference
Fuel-wood	28.50 g/kg	380 g/kg	2.95 g/kg	[34]
Kerosene	62 g/kg			[35]
Kerosene		71.50 t/TJ		[19]
LPG	15 g/kg			[35]
LPG		63 t/TJ		[19]

Table 5
Emission coefficient for agricultural residue burning.

Biomass type	CH_4	CO_2	CO	Reference
Emission factor (g/kg)				
Agricultural residue	2.70	1515 ± 177	92 ± 84	[44]
Wheat straw	7.37 ± 2.72		156 ± 22	[45]
Rice straw	5.32 ± 3.08		82 ± 20	[45]
Wheat straw	3.55 ± 2.66	1787 ± 35	28 ± 20	[43]
Wheat stubble			21.1 ± 1.9	[89]
Wheat fire			38.20	[89]
Wheat			44.1 ± 7.4	[89]
Wheat			59.00	[89]
Wheat			35.00	[89]
Cereal waste		1400	35.00	[53]
Wheat residue	2.62–8.97	959–1320	61.1–179	[86]
Wheat residue	0.59–2.04	1540–1615	26–64	[87]
Wheat straw	0.41		34.65	[88]
Default emission ratio				
Agricultural residue	0.01		0.06	[20]

Table 6
Methane emission coefficients for enteric fermentation.
Source: [46].

Source categories	Emission factor (kg/head/year)
Livestock enteric fermentation	
Cattle	
Cattle–crossbred (male), 4–12 months	9.02
Cattle–crossbred (male), 1–3 years	19.67
Cattle–crossbred (male), < 3 years breeding	36.14
Cattle–crossbred (male), Working	36.31
Cattle–crossbred (male), Breeding and working	34.05
Cattle–crossbred (male), Others	26.07
Cattle–crossbred (female), 4–12 months	9.71
Cattle–crossbred (female), 1–3 years	21.31
Cattle–crossbred (female), Milking	38.83
Cattle–crossbred (female), Dry	38.51
Cattle–crossbred (female), Heifer	21.49
Cattle–crossbred (female), Others	23.6
Cattle–indigenous (male), 0–12 months	7.6
Cattle–indigenous (male), 1–3 years	16.36
Cattle–indigenous (male), < 3 years Breeding	34.86
Cattle–indigenous (male), Working	32.94
Cattle–indigenous (male), Breeding and working	29.42
Cattle–indigenous (male), Others	24.37
Cattle–indigenous (female), 4–12 months	7.39
Cattle–indigenous (female), 1–3 years	15.39
Cattle–indigenous (female), Milking	35.97
Cattle–indigenous (female), Dry	29.38
Cattle–indigenous (female), Heifer	22.42
Cattle–indigenous (female), Others	24.1
Buffalo	
Buffalo (male), 0–12 months	5.09
Buffalo (male), 1–3 years	14.78
Buffalo (male), < 3 years Breeding	58.69
Buffalo (male), Working	66.15
Buffalo (male), Breeding and working	54.28
Buffalo (male), Others	60.61
Buffalo (female), 0–1 months	6.06
Buffalo (female), 1–3 years	17.35
Buffalo (female), Milking	76.65
Buffalo (female), Dry	56.28
Buffalo (female), Heifer	36.81
Buffalo (female), Others	38.99
Goat	
Goat (male), < 1 year	2.83
Goat (male), > 1 year	4.23
Goat (female), < 1 year	2.92
Goat (female), < 1 year milking	4.99
Goat (female), < 1 year Dry	4.93
Sheep	
Sheep	3.67
Others	
Others	8.64

of bovines and 0.1 to 6 kg/head/year for manure management of non-bovines were recorded.

- *Rice cultivation*: Methane emission from rice cultivation is estimated for year 2004–05. Emission from rice cultivation was estimated using average zone specific emission coefficients for different types of cultivation [48]. Table 9 lists the emission factors used for this sector.
- *Waste*: Emissions from municipal solid waste depend on the quantity of organic waste. The main GHG emitted from waste is CH_4. Methane emission from organic waste is computed for the year 2001. IPCC guidelines have been used to estimate emission as an average of 70% of the waste is reaching the landfill site [49]. Further, IPCC default factors of methane correction factor, fraction of degradable organic carbon, fraction of degradable organic carbon converted to landfill gas, fraction of methane and carbon fractions are used in estimation. The amount of recovered methane and oxidation factor are assumed to be zero.

Table 7
Methane emission coefficient for manure management.
Source: [44]

Source categories	Emission factor (kg/head/year)
Livestock manure management	
Cattle	
Dairy cattle (Crossbred), Adult	3.3 ± 0.16
Dairy cattle (Indigenous), Adult	2.7 ± 0.13
Non-Dairy cattle (Crossbred), 0–1 year	0.8 ± 0.04
Non-Dairy cattle (Crossbred), 1–2.5 year	1.7 ± 0.08
Non-Dairy cattle (Crossbred), Adult	2.3 ± 0.11
Non-Dairy cattle (Indigenous), 0–1 year	0.8 ± 0.04
Non-Dairy cattle (Indigenous), 1–3 year	2 ± 0.1
Non-Dairy cattle (Crossbred), Adult	2.8 ± 0.14
Buffalo	
Dairy buffalo	3.3 ± 0.06
Non-Dairy buffalo, 0–1 year	1.2 ± 0.02
Non-Dairy buffalo, 1–3 year	2.3 ± 0.04
Non-Dairy buffalo, Adult	2.7 ± 0.05

Table 9
Emission factors for paddy cultivation.
Source: [48].

Paddy cultivation	Integrated Seasonal CH_4 Flux (g/m^2)		
	Max	Mean	Min
Irrigated areas			
Eastern region			
West Bengal	30.6	23.1	16
Bihar	24.9	18.9	13.1
Orissa	15.3	11.8	8.3
Assam	62	46	32
North East States	62	46	32
Southern Region			
Andhra Pradesh	15	11	7
Tamil Nadu	15	11	7
Kerala	15	11	7
Karnataka	15	11	7
Northern Region			
Uttar Pradesh	24.9	18.9	13.1
Punjab	24.9	18.9	13.1
Haryana	24.9	18.9	13.1
Delhi	24.9	18.9	13.1
Western Region			
Madhya Pradesh	15.3	11.6	8
Maharashtra	15.3	11.6	8
Gujarat	15.3	11.6	8
Rajasthan	15.3	11.6	8
All deep water areas	26	19	13
All rain fed or intermittently irrigated areas	5.9	4.3	2.6

Table 8
Methane emission coefficient for manure management.
Source: [20].

States/UT	Annual mean Temp (°C)	Classification	Emission factor (kg/head/year)					
			Sheep	Goat	Horses and Ponies	Donkeys	Camels	Pigs
Livestock manure management (IPCC Tier-I approach)								
Andhra Pradesh	27.9	Warm	0.21	0.22	2.18	1.19	2.56	6
Arunachal Pradesh	18.7	Temperate	0.16	0.17	1.64	0.9	1.92	4
Assam	23.9	Temperate	0.16	0.17	1.64	0.9	1.92	4
Bihar	25	Temperate	0.16	0.17	1.64	0.9	1.92	4
Goa	27.3	Warm	0.21	0.22	2.18	1.19	2.56	6
Gujarat	26.8	Warm	0.21	0.22	2.18	1.19	2.56	6
Haryana	24.5	Temperate	0.16	0.17	1.64	0.9	1.92	4
Himachal Pradesh	16.5	Temperate	0.16	0.17	1.64	0.9	1.92	4
Jammu & Kashmir	12.7	Cool	0.1	0.11	1.09	0.6	1.28	3
Karnataka	25	Temperate	0.16	0.17	1.64	0.9	1.92	4
Kerala	27.3	Warm	0.21	0.22	2.18	1.19	2.56	6
Madhya Pradesh	25	Temperate	0.16	0.17	1.64	0.9	1.92	4
Maharashtra	26.4	Warm	0.21	0.22	2.18	1.19	2.56	6
Manipur	20.4	Temperate	0.16	0.17	1.64	0.9	1.92	4
Meghalaya	18.6	Temperate	0.16	0.17	1.64	0.9	1.92	4
Mizoram	20.6	Temperate	0.16	0.17	1.64	0.9	1.92	4
Nagaland	17.9	Temperate	0.16	0.17	1.64	0.9	1.92	4
Orissa	26.6	Warm	0.21	0.22	2.18	1.19	2.56	6
Punjab	23.7	Temperate	0.16	0.17	1.64	0.9	1.92	4
Rajasthan	25	Temperate	0.16	0.17	1.64	0.9	1.92	4
Sikkim	15	Cool	0.1	0.11	1.09	0.6	1.28	3
Tamil Nadu	26.6	Warm	0.21	0.22	2.18	1.19	2.56	6
Tripura	24.9	Temperate	0.16	0.17	1.64	0.9	1.92	4
Uttar Pradesh	23.6	Temperate	0.16	0.17	1.64	0.9	1.92	4
West Bengal	25	Temperate	0.16	0.17	1.64	0.9	1.92	4
Union Territories	26.2	Warm	0.21	0.22	2.18	1.19	2.56	6
All India			0.18	0.18	1.6	0.96	1.96	4.37

2.1. Quantification of emissions

Electricity production: Electricity installed capacity in the year 2010 [14] and generation (for 2007–08) have been used to compute the emission from coal based thermal power plants. Emissions from gas and diesel based thermal power plants of India were computed based on the total consumption of natural gas and diesel [50] as given in the following equations:

$$E_i = \sum Ele_{gen} \times \sum E_{i,coal} \quad (2)$$

where, E_i=emission of compound (i); Ele_{gen}=electricity generation; $E_{i,coal}$=emission of compound (i) from coal thermal power plant.

$$E_i = \sum Ene_j \times E_{i,j} \quad (3)$$

where, E_i=emission of compound (i); Ene_j=consumption of energy per type (j); $E_{i,j}$=emission of compound (i) from type (j).

Transport: Emissions from road were quantified based on the number of vehicles and distance travelled in a year per unique vehicle type [29,32,33]:

$$E_i = \sum (Veh_j \times D_j) \times E_{i,j,km} \quad (4)$$

where, E_i=emission of compound (i); Veh_j=number of vehicles per type (j); D_j=distance travelled in a year per unique vehicle type (j); $E_{i,j,km}$=emission of compound (i) from vehicle type (j) per driven kilometre.

Industries: Statewise production data of cement and steel industries have been used to compute emission from cement and steel industries for the year 2009 [51]. This is based on the assumption that 1 t production of steel requires 0.6 t of coking coal and 1 t of metallurgical coal. The methodology to estimate the total emission of particular gas from cement and steel industries are given below:

$$E_i = \sum Cem_p \times E_{i,cement} \quad (5)$$

where, E_i=emission of compound (i); Cem_p=cement production; $E_{i,cement}$=emission of compound (i) from cement industry.

$$E_i = \sum Ste_{coal,j} \times E_{i,j} \quad (6)$$

where, E_i=emission of compound (i); $Ste_{coal,j}$=consumption of coal per type (j) in steel production; $E_{i,j}$=emission of compound (i) from coal type (j).

Domestic energy: Per capita domestic energy consumption values were used for knowing the consumption of energy in cooking activities. As per Census, 2001, Fuelwood and chips are used in 75% of rural and 22% of urban population, similarly 5% of rural and 44% of urban population use LPG. Also, 3% of rural and 22% of urban population use kerosene in their houses [14]. The total emission of GHG from domestic energy consumption is given by the following equation:

$$E_i = \sum Ene_j \times E_{i,j} \quad (7)$$

where, E_i=emission of compound (i); Ene_j=consumption of energy per type (j); $E_{i,j}$=emission of compound (i) from type (j).

Agriculture: Agricultural residue burning: during 2005–06, production of rice, wheat, maize, groundnut, potatoes, soybean and barley are 91.79, 69.35, 14.58, 7.99, 23.91, 8.27 and 1.22 mt respectively [50,52,53]. Around 332.90 mt of agricultural residues are generated from these seven major crops of India. The methodology to estimate the total emissions of a particular gas from agricultural residue burning is given below:

$$E_i = \sum (Agr_j \times R_{1,j} \times R_{2,j} \times D_j \times F_{1,j} \times F_{2,j} \times E_{i,j,kg}) \quad (8)$$

where, E_i=emission of compound (i); Agr_j=kg production from agriculture per type (j); $R_{1,j}$=residue ratio of crop (j); $R_{2,j}$=residue burning ratio of crop (j); D_j=dry matter fraction; $F_{1,j}$=fraction of crop (j) actually burned; $F_{2,j}$=fraction actually oxidised in crop (j); $E_{i,j,kg}$=emission of compound (i) from crop type (j) per kg.

Livestock: Livestock includes all sizes of cattle, buffaloes, sheep, goats, pigs, horses, mules, donkeys and camels. As per district census livestock provisional data of 2003, India has 179.82 million cattle, 97.92 million buffaloes, 61.47 million sheep and 124.36 million goats [52]. The methodology to estimate the total emission of methane from livestock is given by the following equation:

$$E_i = \sum (Liv_j \times E_{i,j}) \quad (9)$$

where, E_i=emission of compound (i); Liv_j=number of livestock per type (j); $E_{i,j}$=emission of compound (i) from livestock type (j) per head

Rice cultivation: The area for Indian rice cultivation was about 41.91 Mha during 2004–05 [54] and it was divided into three categories, namely, irrigated, deepwater and rainfed [55]. Emissions from rice cultivation are computed by the following equation:

$$E_i = \sum (Paddy_j \times E_{i,j,sqm}) \quad (10)$$

where, E_i=emission of compound (i); $Paddy_j$=area of rice cultivation per type (j); j=type of cultivation (Irrigated, deepwater and rainfed); $E_{i,j,sqm}$=emission of compound (i) from rice cultivation type (j) per sqm.

Waste: The rate of municipal solid waste disposal varies from one state to another state. Statewise waste generated is computed using population statistics and average rate of statewise city waste generation. Emission from waste is estimated by the following equation:

$$E_i = \sum \left(Waste_j \times F_1 \times M \times F_2 \times F_3 \times F_4 \times C \right) \quad (11)$$

where, E_i=emission of compound (i); $Waste_j$=kg waste generated in year (j); F_1=fraction of waste disposed at landfill site; M=methane correction factor; F_2=fraction of degradable organic carbon; F_3=fraction of degradable organic carbon converted to landfill gas; F_4=fraction of methane; C=Carbon fraction

2.2. Quantification of carbon sequestration potential

Carbon sequestration refers to the withdrawal of atmospheric carbon dioxide through soil and trees, and storing the carbon in soil in the form of soil organic matter or as tree biomass in trees. Soils in the forest and agriculture sector have been considered as a potential option to mitigate enhanced level of GHG. Estimates indicate that globally soils store about 16×10^5 Tg of carbon and organic matter constitutes about 5–8% in most soil types depending on the rooting depth.

Agricultural soil: Indian agricultural fields used for growing cereals and pulses cover an area of 112.01 Mha [14] and annually, 0.05 mg/ha of carbon is stored in agricultural soil. This value has been considered to compute the total carbon stored in agricultural soil [56].

Forest soil: Indian forest had covered an area of 67.71 Mha in 2005 [16], which is used to deduce the carbon storage in the year 2005. Annual carbon stored in one hectare was 0.3 t. This value is used to compute the carbon stored in forest soil [57].

Forest biomass: Indian forest covers an area of 67.71 Mha in 2005, which is categorised into 14 different groups based on the statewise forest area available for 1987 [16]. The standing biomass [58–66] and average crown cover of different groups of forests are used to calculate total standing biomass. Annual net biomass accumulation and carbon uptake is computed based on

the percentage of net primary productivity [58,64,67,68] of different forests as per the following equation:

$$S_j = Forest_j \times SB_j \times CC_j \times NPP_j \times C \quad (11)$$

where, S_j=annual carbon stored in (j) type of forest; $Forest_j$=forest area occupied by (j) type of forest; SB_j=standing biomass of forest type (j); CC_j=crown cover of forest type (j); NPP_j=net Primary productivity of forest type (j); C=carbon content of biomass.

2.3. Carbon status

The carbon status, which is the ratio of annual carbon storage and carbon emission for each federal state, is computed. Emission of carbon in the form of CO_2, CO and CH_4 are converted into its equivalent of CO_2. Global warming potential of CH_4 is 21 times greater than CO_2. Emissions of CO_2, CO and CH_4 converted into its equivalent of CO_2 was used to compute the carbon status of each state and union territory.

3. Results and discussion

Global sectoral analysis of GHG emission from 1970 to 2004 [69] shows that CO_2 is the major GHG. The per capita GHG emissions in India are still a fraction of the emissions produced by the developed industrialised countries such as US, Russia and Japan [70]. Developing countries with 80% of the world's population account for about one fifth of the cumulative emissions since 1751; the poorest countries in the world, with 800 million people, have contributed less than 1% of these cumulative emissions [19,71]. In order to implement appropriate mitigation and adaptation strategies at local level, knowledge of region wise estimation of GHG emissions is required along with the scope for sequestration of carbon.

Carbon emission: An attempt has been made to compile sector wise emissions from agriculture (agricultural residue burning, rice cultivation and livestock), domestic energy consumption (fuelwood and chips, kerosene and LPG), industries (cement and steel producers), electricity generation and transport.

Electricity generation is one of the major contributors of CO_2 and CO emission; it contributed 35.5% of total CO_2 emission in

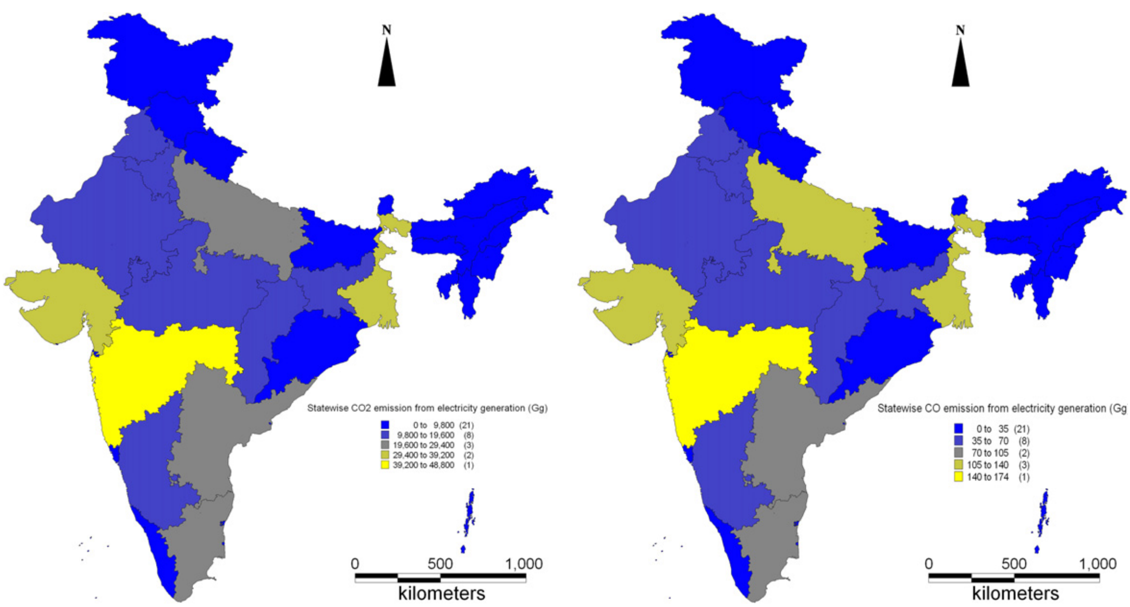


Fig. 2. Statewise emission from electricity generation.

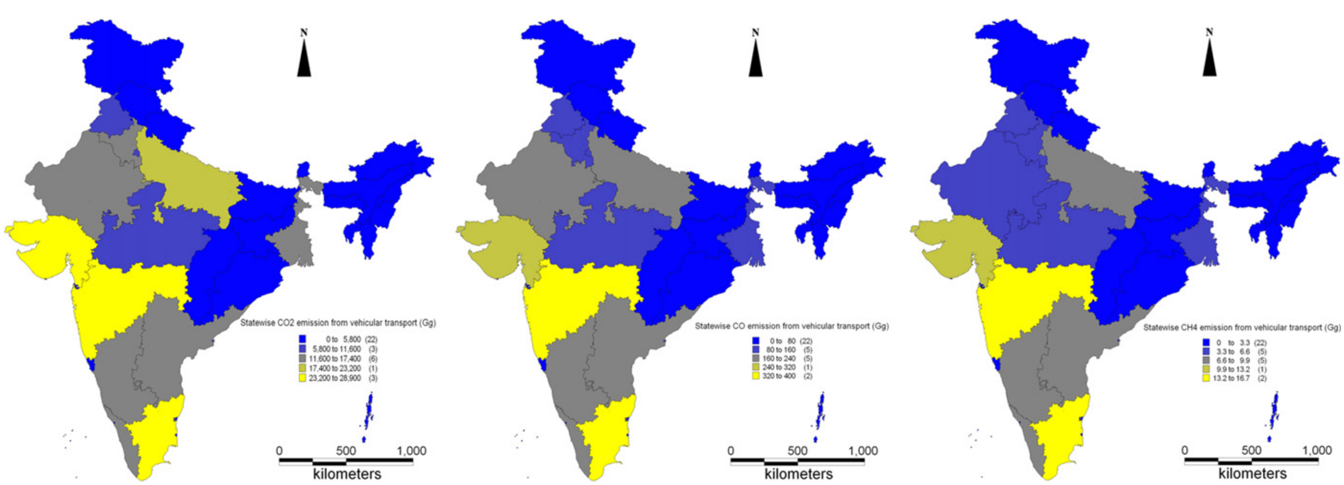


Fig. 3. Statewise emission from vehicular transport.

year 2010. An earlier study done in 2000 shows that CO_2 emission from coal based power plants was 50.1% of the total emission [72]. The current decrease in CO_2 emission could be due to a more efficient means of production and usage of electricity. Total emission from this sector is 343.3 Tg/year for CO_2 and 1.2 Tg/year for CO. Largest percentage of CO_2 and CO emission is contributed by Maharashtra, which is followed by West Bengal and Gujarat as shown in Fig. 22.1 and 2.2.

Indian road transport contributed a significant quantity of 246.2 Tg CO_2 and smaller quantities of CO and CH_4 in the year 2004–05, as given in Fig. 33.1–3.2 respectively. Among the states and UT, Maharashtra's annual contribution was the largest, amounting to 28.8 Tg of CO_2, followed by Tamil Nadu (26.4 Tg), Gujarat (23.3 Tg) and Uttar Pradesh (17.4 Tg). Among all states or UT of India, gross state domestic product (GSDP) of Maharashtra is the highest (Table 10).

Cement and steel industries are major sources of industrial CO_2 emissions. Rajasthan, Andhra Pradesh, Tamil Nadu and Madhya Pradesh are major producers of cement, accounting to about 57% of total cement produced in period April–December, 2009 [51]. Steel industries are basically distributed in Chattisgarh, Jharkhand, Maharashtra and Gujarat. In steel industries usually both types of coal: coking coal as well as metallurgical coal is used. Coking coal emits more carbon than metallurgical coal. Total contribution of this sector is 202.2 Tg/year as shown in Fig. 4. Jharkhand (26.1 Tg/year), Chhattisgarh (26.1 Tg/year), Andhra Pradesh (20.1 Tg/year), Maharashtra (17.3 Tg/year) and

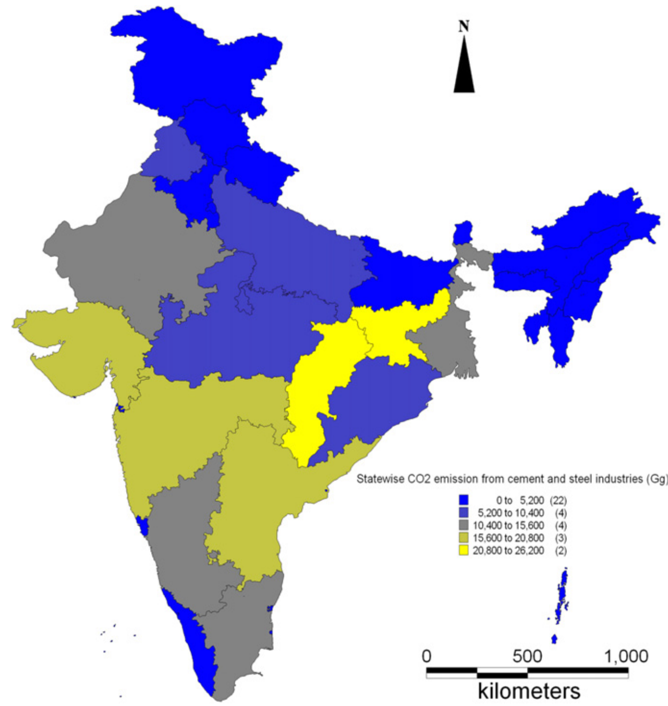


Fig. 4. Statewise CO_2 emission from cement and steel industries.

Table 10
Statewise growth and development indicators.
Source: #[91], *[92], **[85], ***[23] and +[50].

State/UT	Population#		GSDP (Rs. in crores)*	Per capita income (Rs)*	No. of registered motor vehicles**	Installed capacity (MW)***				Industrial production (kt)+	
	Rural	Urban				Coal	Gas	Diesel	Hydro	Cement	Steel
Andaman and Nicobar Islands	239,954	116,198	2982	54,992	28,456	0	0	60	0	0	0
Andhra Pradesh	55,401,067	20,808,940	381,942	40,366	5,719,920	5274	1285	37	3576	21,532.5	3105.2
Arunachal Pradesh	870,087	227,881	5691	37,417	21,144	0	21	0	117	0	0
Assam	23,216,288	3,439,240	74,215	21,406	726,819	330	447	21	333	105.8	152.6
Bihar	74,316,709	8,681,800	144,472	13,632	750,703	1532	0	0	66	462.6	221.9
Chandigarh	92,120	808,515	15,754	99,487	586,107	20	15	2	37	0	138.8
Chhattisgarh	16,648,056	4,185,747	79,166	27,156	1,215,745	1490	0	0	120	7402.2	7481.7
Dadra and Nagar Haveli	170,027	50,463	NA	NA	35,115	9	27	0	0	0	360.6
Daman and Diu	100,856	57,348	NA	NA	48,300	8	4	0	0	0	194.2
Delhi	944,727	12,905,780	191,696	108,876	4,236,675	2167	817	0	395	0	55.5
Goa	677,091	670,577	20,922	102,844	436,120	257	48	0	0	0	402.3
Gujarat	31,740,767	18,930,250	365,295	52,708	7,087,490	5773	2320	17	617	10,602.8	3596.5
Haryana	15,029,260	6,115,304	166,095	59,221	2,547,910	1934	532	4	1318	1397.8	763.2
Himachal Pradesh	5,482,319	595,581	39,066	47,106	288,813	72	61	0	1432	1836.2	208.0
Jammu and Kashmir	7,627,062	2,516,638	38,739	27,607	438,596	149	302	9	864	113.9	110.9
Jharkhand	20,952,088	5,993,741	78,045	21,734	1,216,958	3179	45	0	213	2994.7	8241.9
Karnataka	34,889,033	17,961,529	279,932	39,301	3,976,584	2750	220	234	3376	7131.7	2819.4
Kerala	23,574,449	8,266,925	193,383	49,873	2,792,074	728	524	256	1818	288.6	679.7
Lakshadweep	26,967	26,967	NA	NA	5371	0	0	10	0	0	0
Madhya Pradesh	44,380,878	15,967,145	182,647	22,382	3,803,528	3215	253	0	2131	14,610.3	319.1
Maharashtra	55,777,647	41,100,980	775,020	62,729	8,968,733	9414	2229	0	3009	8481.3	4359.9
Manipur	1,717,928	575,968	7184	23,298	106,325	0	26	45	83	0	0
Meghalaya	1,864,711	454,111	10,736	35,932	73,382	0	26	2	241	1133.0	138.7
Mizoram	447,567	441,006	4557	36,732	42,145	0	16	52	38	0	0
Nagaland	1,647,249	342,787	8591	40,957	171,917	0	19	2	79	0	0
Orissa	31,287,422	5,517,238	128,367	25,708	1,524,982	1551	0	0	1870	3081.5	2887.9
Puducherry	648,619	648,619	10,318	79,333	312,950	200	33	0	0	0	374.5
Punjab	16,096,488	8,262,511	148,844	44,752	3,529,100	2591	260	0	3045	2941.1	2108.7
Rajasthan	43,292,813	13,214,375	196,045	25,616	3,833,806	2971	332	0	1335	22,872.5	429.9
Sikkim	480,981	59,870	3642	47,655	17,236	60	0	5	40	0	0
Tamil Nadu	34,921,681	27,483,998	391,372	51,928	8,575,241	5499	832	412	1996	15,649.7	1081.8
Tripura	2,653,453	545,750	14,203	37,216	75,547	0	140	5	78	0	0
Uttar Pradesh	131,658,339	34,539,582	394,499	17,349	6,460,198	6248	541	0	1082	4721.1	2011.3
Uttarakhand	6,310,275	2,179,074	51,107	44,723	515,982	206	68	0	1080	257.4	388.4
West Bengal	57,748,946	22,427,251	317,786	32,228	2,547,963	6597	145	12	254	3028.7	3141.9

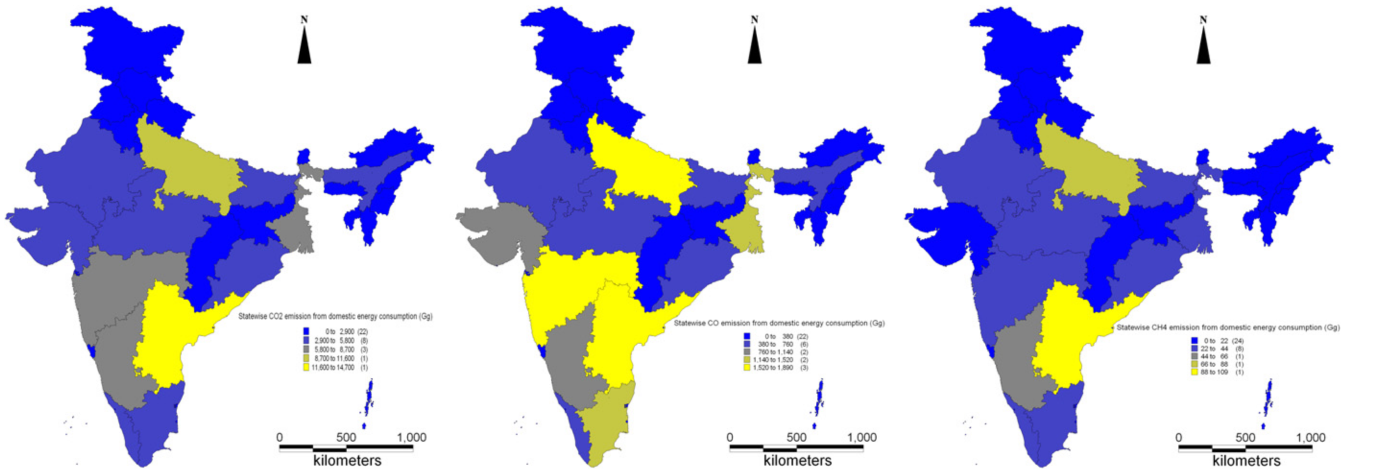


Fig. 5. Statewise emission from domestic energy consumption.

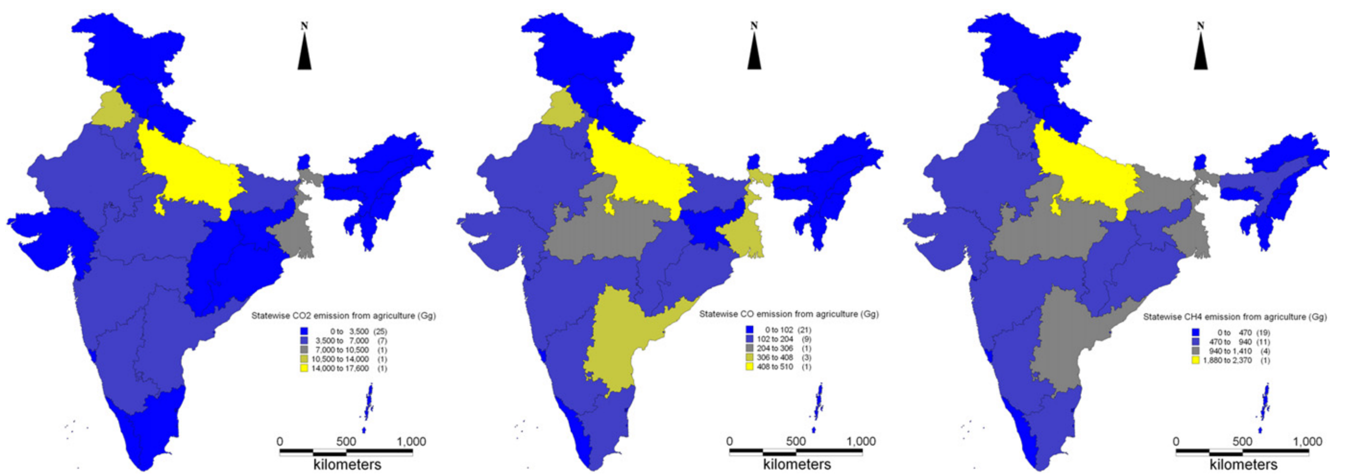


Fig. 6. Statewise emission from agriculture.

Gujarat (16.1 Tg/year), with major cement and steel industries contribute 52% of total CO_2 emission from the industrial sector.

Domestic energy consumption (rural and urban consumption) contributes 88.3 Tg/year, 14.7 Tg/year and 0.6 Tg/year of CO_2, CO and CH_4 respectively in the year 2001, as illustrated in Fig. 55.1–5.2 respectively. CO_2 emission is largest in Andhra Pradesh (14.6 Tg/year) followed by Uttar Pradesh (9.9 Tg/year), and Maharashtra (6.5 Tg/year). Census of India, 2001 shows that Andhra Pradesh, Uttar Pradesh and Maharashtra have highest population as compared to other states of India. Similarly, CO emission is highest in Maharashtra (1.8 Tg/year), followed by Andhra Pradesh (1.6 Tg/year) and Uttar Pradesh (1.6 Tg/year).

Indian agriculture contributes to significant quantities of 85.8 Tg CO_2 and smaller quantities of CH_4 and CO. Annual CO_2, CH_4 and CO emission in the agriculture sector, quantified based on agricultural area and production and number of livestock, is given in Fig. 66.1–6.2. It illustrates that agriculturally dominant states are Uttar Pradesh, Punjab, West Bengal, Madhya Pradesh, and Andhra Pradesh. Emission from agricultural residue burning, livestock and rice cultivation are computed for the years 2005–2006, 2003 and 2004–2005. Uttar Pradesh is contributing a maximum of 17.5 Tg/year of CO_2, followed by Punjab (11.6 Tg/year), West Bengal (7.2 Tg/year), Madhya Pradesh (6.9 Tg/year) and Andhra Pradesh (6.6Tg/year). These states account for 58% of the CO_2 emissions from agriculture. Agricultural residue burning is a major contributor of CO_2 emission in Agriculture. Livestock and rice cultivation are major cause of methane emission. Uttar Pradesh (2.3 Tg/year) leads in contributing methane followed by West Bengal, Andhra Pradesh and Madhya Pradesh. Similarly, carbon monoxide emission is largest in Uttar Pradesh (0.5 Tg/year), which is followed by West Bengal, Andhra Pradesh and Punjab.

The total methane emitted from municipal solid waste accounts to 0.9 Tg/year. Uttar Pradesh is contributing the largest fraction of 0.1 Tg/year, followed by Maharashtra and Tamil Nadu (Fig. 7). The greater contribution of Uttar Pradesh is because it has an urban population of 34 million and 131 million of rural population (Table 10), which is second highest population in Indian states/UT.

Sector wise analysis of global GHG emission highlights that energy is the major sector of CO_2 emission (25.9%) followed by industries (19.4%) [19]. The current Indian sector wise analysis shows a similar type of trend with the highest contribution of 35.5% from electricity production followed by transport (25.5%) and steel and cement industries (20.9%). During the last two decades, number of registered motor vehicles has also increased dramatically from 5.4 million in 1980–81 to 72.7 million 2003–04 [73]. This has also enhanced the demand of energy. India is following the global urbanisation trend and consequent to this, CO_2 emissions have doubled between 1990 and 2008 and a large share is taken by the electricity and heat sector, which represented 56% of CO_2 in 2008 which was 42% in the early nineties

[74,75]. The net GHG emissions from India (emissions with LULUCF) were 1727.71 million tons (mt) of CO_2 equivalent in 2007. Current analysis reveals that, India emits around 965.9 Tg of CO_2, 22.5 Tg of CO and 16.9 Tg of CH_4 annually from different sources. Compared to this, an earlier study (1994) reports of 817 Tg/year CO_2, 18 Tg CH_4 emissions [76] and 69 Tg/year CO emissions of [77]. A similar study in 2005 [78] indicates emissions of 1229 Tg/year of CO_2 and 20.08 Tg/year of CO considering coal mining, aviation and navigation in addition to the sources considered in the present study. This study, nevertheless, provides a decentralised picture of emissions and the ability for sequestration. Sector wise percentage contribution of CO_2, CO and CH_4 are shown in Fig. 8 and Table 11 lists sector wise contribution of CO_2, CO and CH_4 Among all federal states and UT, Maharashtra's contribution is largest in CO_2 and CO emission of 105.2 Tg/yr and 2.6 Tg/yr, respectively and Uttar Pradesh.has higher CH_4 emission of 2.5 Tg/year.

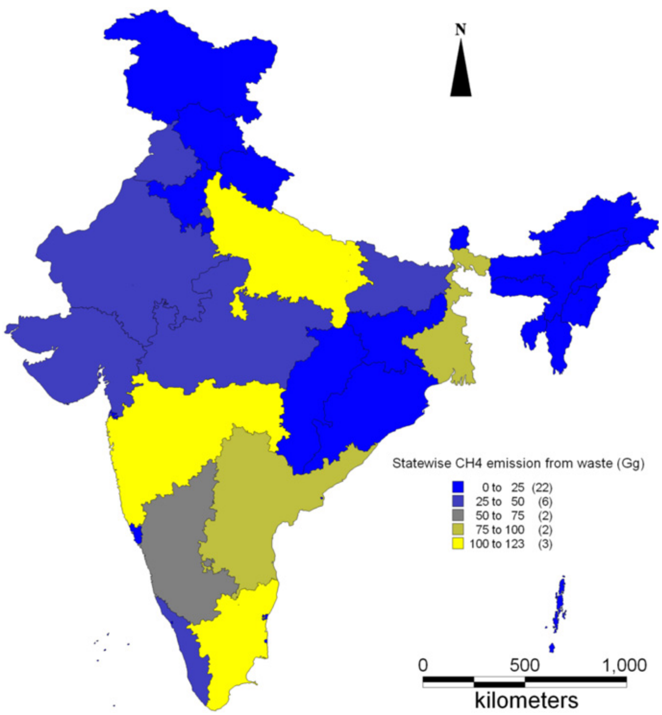


Fig. 7. Statewise emission from municipal solid waste.

Carbon sequestration: Forest vegetation and soil sequester carbon and Fig. 9 highlights the relative share of forests (vegetation, soil) and agriculture (soil) sectors. Base year for the current estimation is 2005 for forest biomass and soil, and 2008 for agricultural soil. During 1995 to 2005, carbon stocks in forest vegetation have increased from 6245 to 6662 mt, registering an annual increment of 38 mt of carbon or 138 mt of CO_2 equivalents. Estimates reveal that forests have neutralised about 11.25% of total CO_2 equivalent GHG emissions in year 1994 [79,80]. This is equivalent to offsetting 100% emissions from all energy in residential and transport sectors; or 40% of total emissions from the agriculture sector. Forest biomass store around 74% of total carbon stored. India has a large spread of forest in an area of 67,708 thousand ha. Annually, it accumulates 72.92 Tg of carbon. Arunachal Pradesh and Madhya Pradesh have the largest capacity of 7.99 Tg/year and 7.04 Tg/year of carbon. Forest Soil has second largest potential to accumulate organic carbon. It accumulates 20.31 Tg/year. Madhya Pradesh and Arunachal Pradesh's forest soil have largest capacity of 2.28 Tg/year and 2.03 Tg/year of carbon. Statewise carbon storage potential in agricultural soil, forest soil and forest biomass is given in Fig. 10 and total stored carbon is shown in Fig. 11. Indian agriculture covers 112,009 thousand ha of land area for cultivation of food grains and pulses. Annually it sequesters 5.6 Tg of carbon in soil. Uttar Pradesh has the largest capacity of 0.92 Tg/year of sequestered carbon. Earlier study estimates that organic carbon stored in Indian soil at depths of 0 to 0.3 m is 9500 Tg [81]. Total carbon stored in India is 98.8 Tg/year (Table 12). Among all the states and UTs, Arunachal Pradesh's contribution is the largest of 10 Tg, it is 10% of total carbon stored, followed by Madhya Pradesh and Chhattisgarh.

Carbon status (CS): Statewise Carbon status illustrates the quantity of carbon sequestered compared to the emissions in each federal state or UT. Basically, it is the ratio of carbon sequestered to total carbon emitted, given in Fig. 12, which highlights that Arunachal Pradesh (CS: 7.5), Mizoram (CS: 1.9), Andaman and Nicobar Islands (CS: 1.6) and Manipur (CS: 1.2) are

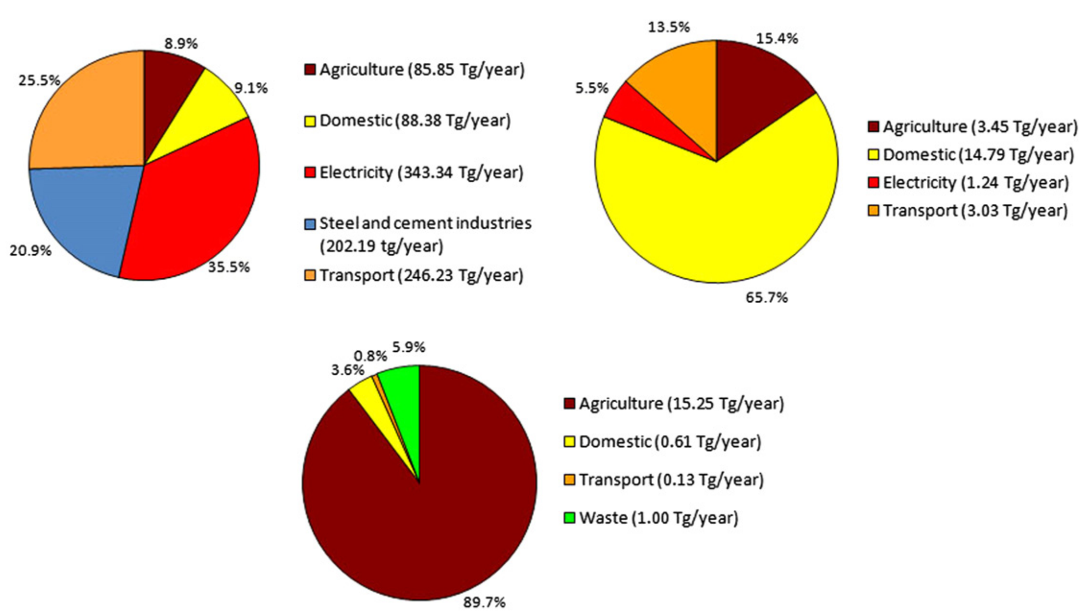


Fig. 8. Sector wise contribution in total Carbon emission (CO_2=987.1 Tg/year, CO=24.7 Tg/year, CH_4=17.0 Tg/year) of India.

Table 11
Sector wise annual carbon emission and sequestration.

Carbon sources	CO_2 (Gg)	CO (Gg)	CH_4 (Gg)	Total CO_2 equivalent emission (Gg)
Agriculture	85851.0	3459.2	15246.9	409495.88
Domestic	88378.5	14798.7	611.5	116018.91
Electricity	343344.5	1237.3	0.0	344581.81
Steel and cement industries	202190.0	0.0	0.0	202190.02
Transport	246232.4	3030.9	127.3	251936.79
Waste	0.0	0.0	995.72	21104.79
Total (Gg)	965996.5	22526.0	16990.8	1345328.2
Carbon sinks				Carbon stored (Gg)
Forest biomass				72916.77
Forest soil				20312.64
Agricultural soil				5600.49
Total (Gg)				98829.89
Net emission				1246498.3

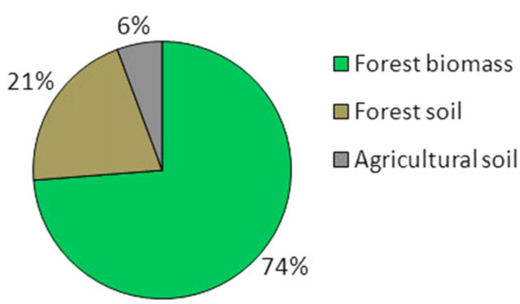


Fig. 9. Contribution of different sectors in Carbon sink.

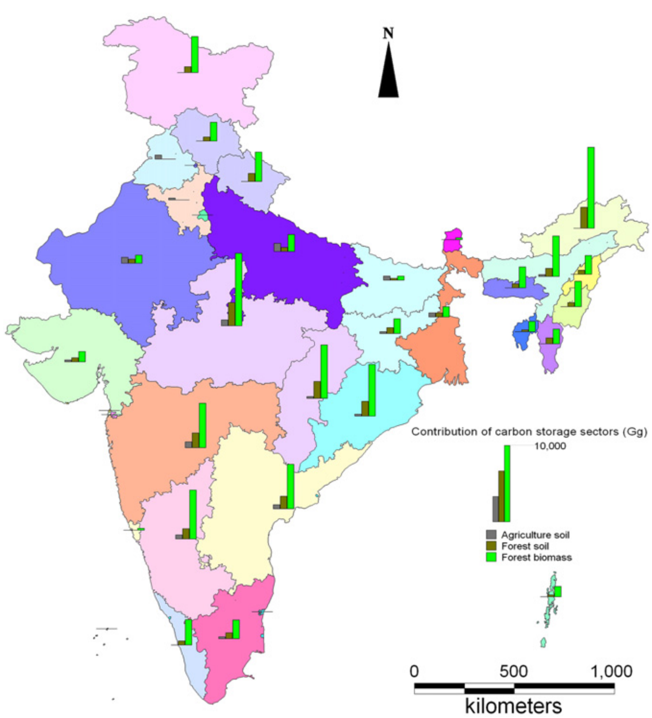


Fig. 10. Statewise annual Carbon stored in sectors.

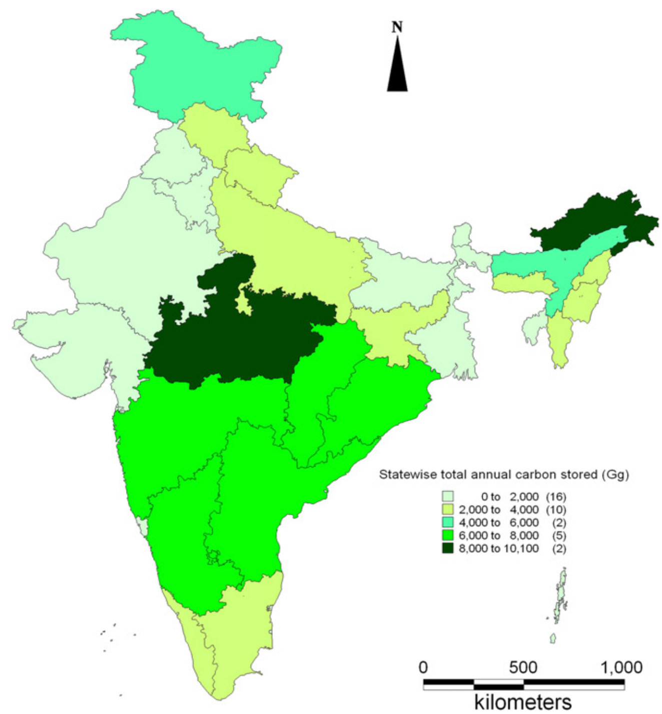


Fig. 11. Statewise annual Carbon stored.

places where the carbon ratio (carbon status) is more than one, indicating higher carbon sequestration than carbon emissions. Arunachal Pradesh has a large spread of forest area in 6.8 mha (million hectare) and total standing biomass is 939 mt, followed by other states like Madhya Pradesh, Orissa and Chhattisgarh with standing biomass of 817 mt, 634 mt and 600 mt, respectively. Carbon ratio of these states is less than one, which highlights that annual carbon emission from all sectors is higher than annual carbon sequestration potential.

Carbon status of a region can be reduced through carbon sequestration. Species of carbon is naturally captured from the atmosphere through biological, chemical or physical processes. Vegetation plays a prominent role in maintaining the balance [80]. Improvements in energy economy has to be through improvements in energy efficiency, use of renewable sources of energy, CO_2 capture and sequestration (CCS) on a massive scale and development of carbon free transport. Use of low carbon footprint biofuels and improvements in the efficiency of vehicles will reduce the carbon from the transport sector [82]. Decarbonsiation in the consumer sector include the design of environment friendly green building (depending on the region's climate), heat pumps, solar heating, use of high efficiency appliances and lighting (CFL: Compact fluorescent lamps, LED: Light emitting Diodes) shifting to renewable (like solar, wind, hydro, bioenergy, etc.), low-carbon electricity, etc. [42,80,82]. Renewable energy

Table 12
Statewise total carbon emission and carbon storage.

State/UT	Emission (Gg)			Carbon storage (Gg)
	CH_4	CO	CO_2	
Andaman and Nicobar Islands	4.9	11.4	618.0	1186.8
Andhra Pradesh	1441.5	2308.8	82758.3	6115.2
Arunachal Pradesh	35.7	24.1	561.2	10038.2
Assam	663.7	518.3	10625.8	4900.3
Bihar	995.0	916.9	18582.2	852.7
Chandigarh	5.5	47.2	1442.6	1.3
Chhattisgarh	571.4	448.6	50157.8	7066.8
Dadra and Nagar Haveli	2.2	6.3	1457.7	35.7
Daman and Diu	0.6	3.9	846.9	1.5
Delhi	85.3	175.2	23517.4	17.2
Goa	11.1	33.7	3881.2	366.1
Gujarat	740.3	1449.8	79137.8	1604.2
Haryana	546.8	453.7	35034.5	340.8
Himachal Pradesh	125.3	116.4	5376.6	2436.0
Jammu and Kashmir	180.9	195.6	6387.8	4283.2
Jharkhand	507.2	495.0	46265.9	2264.5
Karnataka	745.8	1523.9	54336.5	6166.5
Kerala	150.8	610.8	26046.5	2927.2
Lakshadweep	0.4	1.9	105.8	4.5
Madhya Pradesh	1100.1	1171.9	47650.8	9842.4
Maharastra	1101.4	2649.7	105259.9	6419.0
Manipur	61.6	29.4	1032.1	2927.3
Meghalaya	58.7	37.5	2049.7	2589.0
Mizoram	11.7	16.8	823.4	2093.1
Nagaland	57.6	47.8	2525.8	2375.7
Orissa	833.9	771.9	29368.6	6758.9
Pondicherry	7.0	20.9	2848.6	3.3
Punjab	924.7	772.9	44827.7	431.8
Rajasthan	973.0	983.3	54463.5	1876.9
Sikkim	6.1	7.1	432.3	382.1
Tamil Nadu	750.5	1919.0	71107.4	2611.6
Tripura	70.6	65.2	1085.3	1294.7
Uttar Pradesh	2567.6	2473.8	80683.0	3086.0
Uttarakhand	181.4	144.5	4987.7	3795.8
West Bengal	1461.0	2072.6	69709.9	1733.3
Total	16981.5	22526.0	965996.4	98829.9

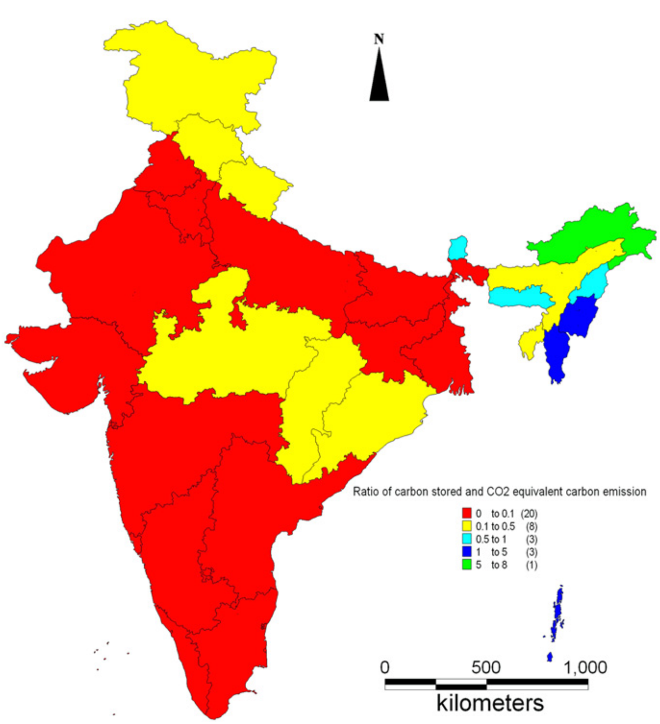


Fig. 12. Ratio of Carbon stored to CO_2 equivalents.

resources, which the country has in abundance, such as solar, wind, biomass, small hydro, etc. can effectively meet energy demand and are environmentally benign. About 5200 MW of power generating capacity based on renewable energy sources has been installed in the country so far [17,83]. This constitutes about 3.8% of the total installed capacity. It is observed that nearly 58% of the country receives annual average Global insolation of 5 kWh/m^2/day which if exploited could meet power requirements in a decentralised, efficient and sustainable manner [84].

Conclusions

Most of Indian or global inventories are either estimated at national level or inventory considers only emission sources without including carbon storage potential or vice-versa. This article provides a decentralised carbon inventory, which will aid in planning the GHG mitigation and management strategies at local levels. A good carbon inventory needs to consider both carbon emission as well as storage capacity. Hence, the present effort consists of a statewise inventory where major contributors of carbon emission are included along with major carbon sinks of India. The total CO_2 emission from India is 965.9 Tg/year. Among all the sectors, electricity generation, transport, and cement and steel industries were first, second and third major contributors of CO_2 emission. Among all the states and UTs, Maharashtra's contribution is the largest in CO_2 and CO emissions and Uttar Pradesh contributes the highest CH_4 emission. In terms of carbon storage potential, Arunachal Pradesh is the major carbon sink of India. Ratio of carbon sequestration to carbon emission in terms of it equivalent in carbon dioxide is also highest for Arunachal Pradesh (CS: 7.5), which is followed by Mizoram, Andaman and Nicobar Islands, and Manipur, which shows that carbon storage capacity is more than emission.

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